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(54) **USING CLUSTERING TECHNIQUES TO
IMPROVE MAGNETOMETER BIAS
ESTIMATION**

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(56) **References Cited**

U.S. PATENT DOCUMENTS

5,075,693 A 12/1991 McMillan et al.
5,165,269 A 11/1992 Nguyen
5,349,529 A 9/1994 Masumoto et al.
5,761,094 A 6/1998 Olson et al.

(Continued)

FOREIGN PATENT DOCUMENTS

EP 1 221 586 7/2002
JP 2005-134343 5/2005

(Continued)

OTHER PUBLICATIONS

"Honeywell 3-Axis Digital Compass IC, HMC5843 Electronic
Compass," Honeywell International Inc. [online]; retrieved from the
Internet: <URL: <http://www.honeywell.com/sites/portal?smap=aerospace&page=Magnetic-Sensors3&theme=T15&catID=CF84B17AB-A90F-716D-10BC-A1E75441138E&id=HF916B4E0-4F71-9DB5-DFA8-51B1944918EE&sel=2&sel4=1>>, retrieved on Jun. 5, 2005, 1 page.

(Continued)

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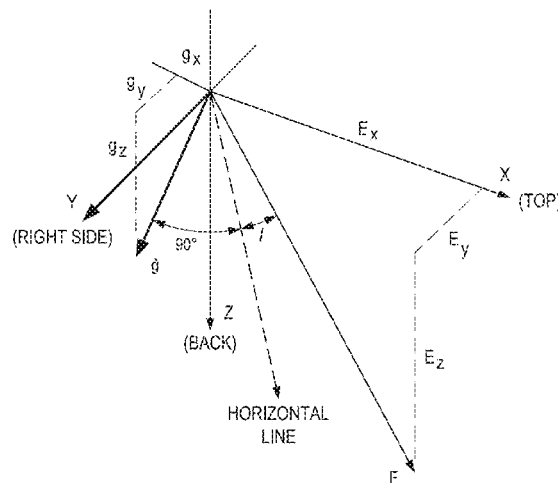
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ABSTRACT

In some implementations, a computer-implemented method includes receiving a reading from a magnetometer of a mobile device. A cluster from a plurality of clusters of bias offsets generated from previously-calibrated readings is selected. The selected cluster has a representative bias offset, a mean of magnitudes in the selected cluster, and a magnitude threshold. An external magnetic field is estimated based on the reading and the representative bias offset for the selected cluster. Whether a magnitude of the estimated external field is within a magnitude range defined by the mean magnitude and the mean magnitude plus the magnitude threshold is determined.

26 Claims, 6 Drawing Sheets



(56)

References Cited

U.S. PATENT DOCUMENTS

5,946,813 A 9/1999 Nachbaur et al.
 6,204,804 B1 3/2001 Andersson
 6,311,098 B1 10/2001 Higashiyama et al.
 6,311,129 B1 10/2001 Lin
 6,384,384 B1 5/2002 Connolly et al.
 6,408,245 B1 6/2002 An et al.
 6,424,914 B1 7/2002 Lin
 6,508,316 B2 1/2003 Estes et al.
 6,539,639 B2 4/2003 Smith
 6,622,091 B2 9/2003 Perlmutter et al.
 6,651,003 B2 11/2003 Woloszyk et al.
 6,768,452 B2 7/2004 Gilkes
 6,807,485 B1 10/2004 Green
 6,834,528 B2 12/2004 Kappi et al.
 6,964,107 B1 11/2005 Ahola
 6,988,049 B1 1/2006 Wirtz et al.
 7,196,660 B2 3/2007 Abraham
 7,210,236 B2 5/2007 Sato et al.
 7,248,983 B2 7/2007 Fillatreau et al.
 7,275,008 B2 9/2007 Plyvanainen
 7,324,906 B2 1/2008 Sato et al.
 7,331,115 B2 2/2008 Schierbeek et al.
 7,346,452 B2 3/2008 Ford et al.
 7,388,541 B1 6/2008 Yang
 7,391,366 B2 6/2008 Park et al.
 7,400,974 B2 7/2008 Fuchs et al.
 7,415,354 B2 8/2008 Alexander
 7,451,549 B1 11/2008 Sodhi et al.
 7,458,166 B2 12/2008 Parks et al.
 7,548,200 B2 6/2009 Garin
 7,565,839 B2 7/2009 Stewart et al.
 7,891,103 B2 2/2011 Mayor et al.
 8,061,049 B2 11/2011 Mayor et al.
 8,432,156 B2 4/2013 Almalki et al.
 8,437,970 B2 5/2013 Mayor et al.
 2003/0135327 A1 7/2003 Levine et al.
 2005/0154532 A1 7/2005 Close et al.
 2005/0174324 A1 8/2005 Liberty et al.
 2005/0223575 A1 10/2005 Fillatreau et al.
 2005/0240347 A1 10/2005 Yang
 2005/0246099 A1 11/2005 Jendbro et al.
 2005/0288805 A1 12/2005 Moore
 2006/0066295 A1 3/2006 Tamura et al.
 2006/0190174 A1 8/2006 Li et al.
 2006/0195254 A1 8/2006 Ladetto et al.
 2006/0212182 A1 9/2006 Shaw
 2006/0271295 A1 11/2006 McLaren et al.
 2007/0103461 A1 5/2007 Suzuno et al.
 2007/0156337 A1 7/2007 Yanni
 2008/0066331 A1 3/2008 Brzezinski et al.
 2008/0143595 A1 6/2008 Colley et al.
 2008/0147686 A1 6/2008 Colley et al.
 2008/0201096 A1 8/2008 Wright et al.
 2009/0033807 A1 2/2009 Sheng et al.
 2009/0054075 A1 2/2009 Boejer
 2009/0070058 A1 3/2009 Lin
 2009/0089001 A1 4/2009 Lin
 2009/0164067 A1 6/2009 Whitehead et al.
 2009/0171607 A1 7/2009 Chen et al.
 2009/0172599 A1 7/2009 Nezu
 2009/0326851 A1 12/2009 Tanenhaus
 2010/0121599 A1 5/2010 Boeve et al.
 2010/0188276 A1 7/2010 Griffith et al.
 2010/0305853 A1 12/2010 Schulze et al.

2011/0106474 A1 5/2011 Kulik et al.
 2012/0206129 A1 8/2012 Mahan et al.
 2013/0320966 A1* 12/2013 Oliver et al. 324/202
 2014/0361763 A1* 12/2014 Chow et al. 324/202

FOREIGN PATENT DOCUMENTS

JP 2006-058060 3/2006
 JP 2009-192495 8/2009
 JP 2010-054431 3/2010
 WO WO 2005/040991 5/2005
 WO WO 2008/122904 10/2008
 WO WO 2009/068116 6/2009

OTHER PUBLICATIONS

Adiprawita et al., "Development of AHRS (Attitude and Heading Reference System) for Autonomous UAV (Unmanned Aerial Vehicle)," *Proc Int'l Conf Electrical Engineering and Informatics*, Institut Teknologi Bandung, Indonesia, Jun. 17-19, 2004, 4 pages.
 An Overview of the Earth's Magnetic Field, "The Earth's Magnetic Field—An Overview", [Online] [Retrieved on May 16, 2009]. Retrieved from the Internet: URL: <http://www.geomag.bgs.ac.uk/earthmag.html>, 10 pages.
 Apptism, Compass Go, © 2009 Apptism, [Online] [Retrieved on Jun. 3, 2009]. Retrieved from the Internet: URL: <http://www.apptism.com/apps/compass-go>, 2 pages.
 Apptism, Focalware, © 2009 Apptism, [Online] [Retrieved on Jun. 3, 2009]. Retrieved from the Internet: URL: <http://www.apptism.com/apps/focalware>, 2 pages.
 Apptism, iTopoMaps, © 2009 Apptism, [Online] [Retrieved on Jun. 2, 2009]. Retrieved from the Internet: URL: <http://www.apptism.com/apps/itopomaps>, 4 pages.
 Authorized officer Adina-Gabriela Otinjac, International Search Report/Written Opinion mailed May 25, 2011, 22 pages.
 Authorized officer Luis-Miguel Paredes Sanchez, Invitation to Pay Additional Fees and, where applicable, protest fee, in PCT/US2010/050219 mailed Jan. 19, 2011, 5 pages.
 Camps et al., "Numerical Calibration for 3-Axis Accelerometers and Magnetometers," *IEEE*, 2009, pp. 217-231.
 Chris M. Goulet, "Magnetic Declination, Frequently Asked Questions", Oct. 2001, Version 4.4, [Online] [Retrieved on May 16, 2009]. Retrieved from the Internet: URL: http://www.geocities.com/magnetic_declination/, 16 pages.
 Harper et al., "Process for Improving GPS acquisition assistance data and server-side location determination for cellular networks," *2004 Intl Symp on GNSS/GPS*, Dec. 6-8, 2004, Sydney, Australia, 15 pages.
 PNI Sensor Corporation, "Calibration Computations for Practical Compassing using the PNI-11096 Magnetometer ASIC", Aug. 2008, PNI Corporation © 2001, Santa Rosa, CA, 3 pages.
 Seong Yun Cho et al., "A Calibration Technique for a Two-Axis Magnetic Compass in Telematics Devices", Jun. 2005, *ETRI Journal*, vol. 27, No. 3, pp. 280-288.
 Westerberg, "Compass Go," Apple Apps Store, Oct. 10, 2008, 3 pages.
 Zhang and Gao, "A Novel Auto-calibration Method of the Vector Magnetometer," *Ninth Intl Conf on Electronic Measurement & Instruments*, ICEMI '2009, pp. 1-145 through 1-150.
 PNI Sensor Corporation, "Multipoint Calibration Primer", Sep. 4, 2010, PNI Corporation, Santa Rosa, CA, 10 pages.

* cited by examiner

FIG. 1

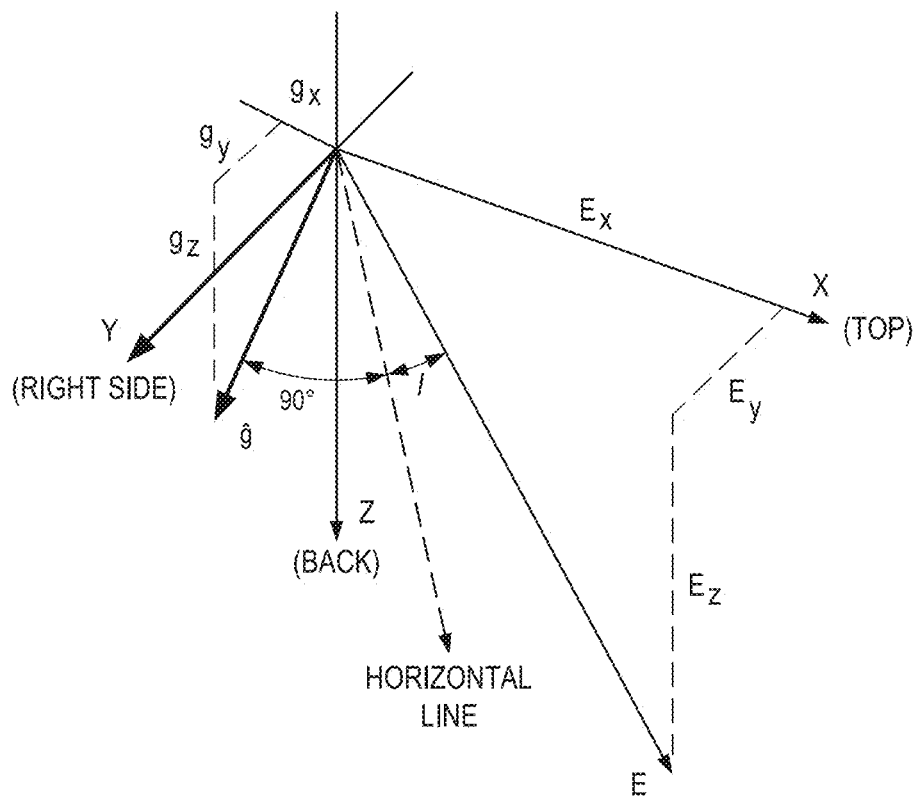
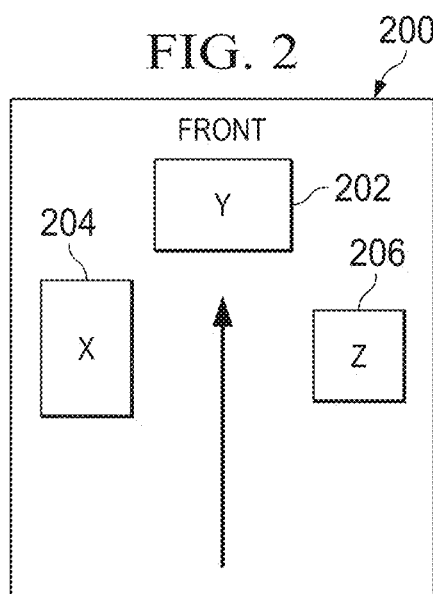


FIG. 2



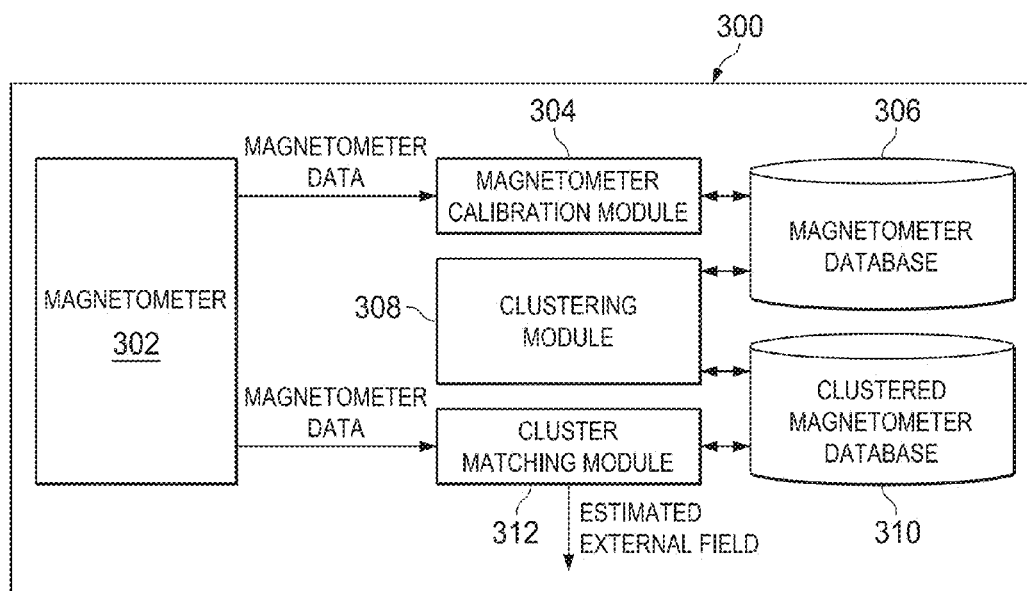


FIG. 3

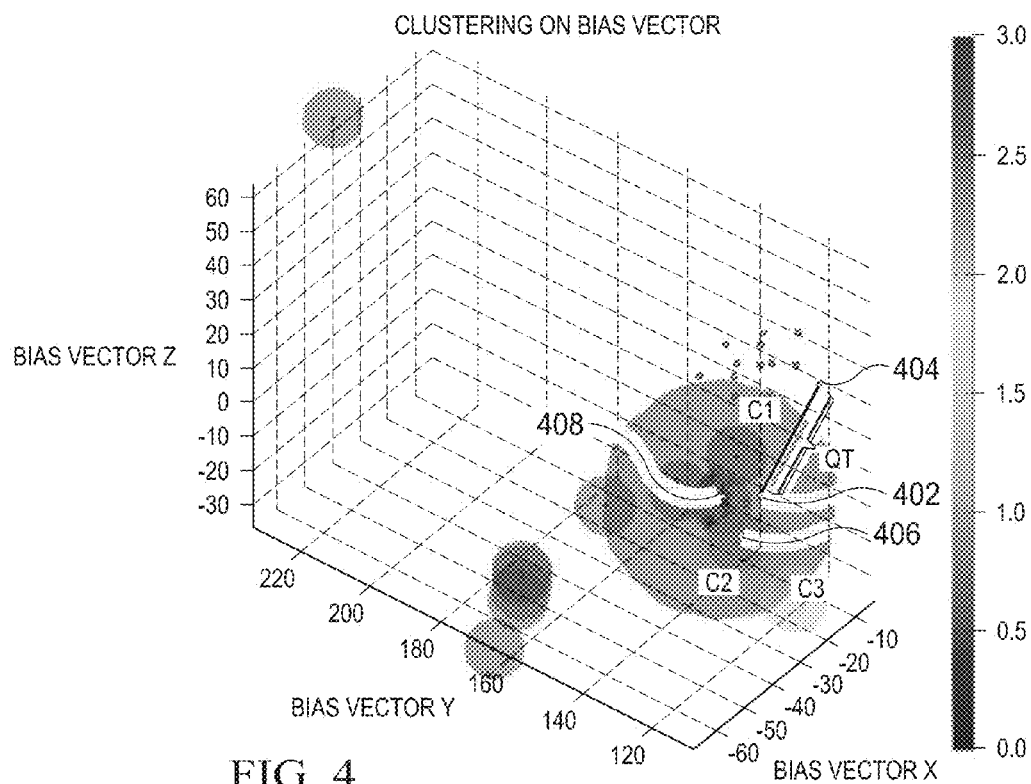


FIG. 4

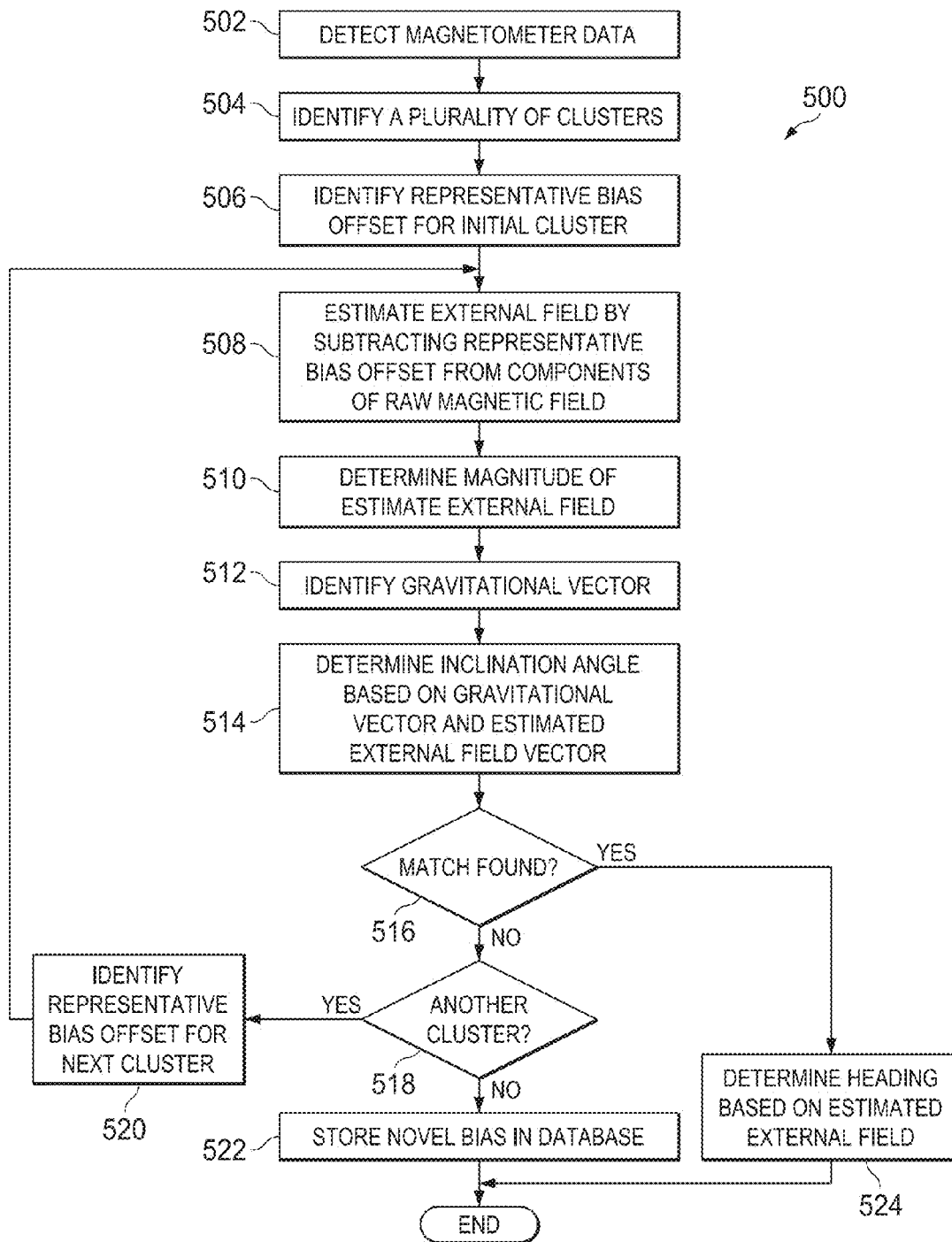


FIG. 5

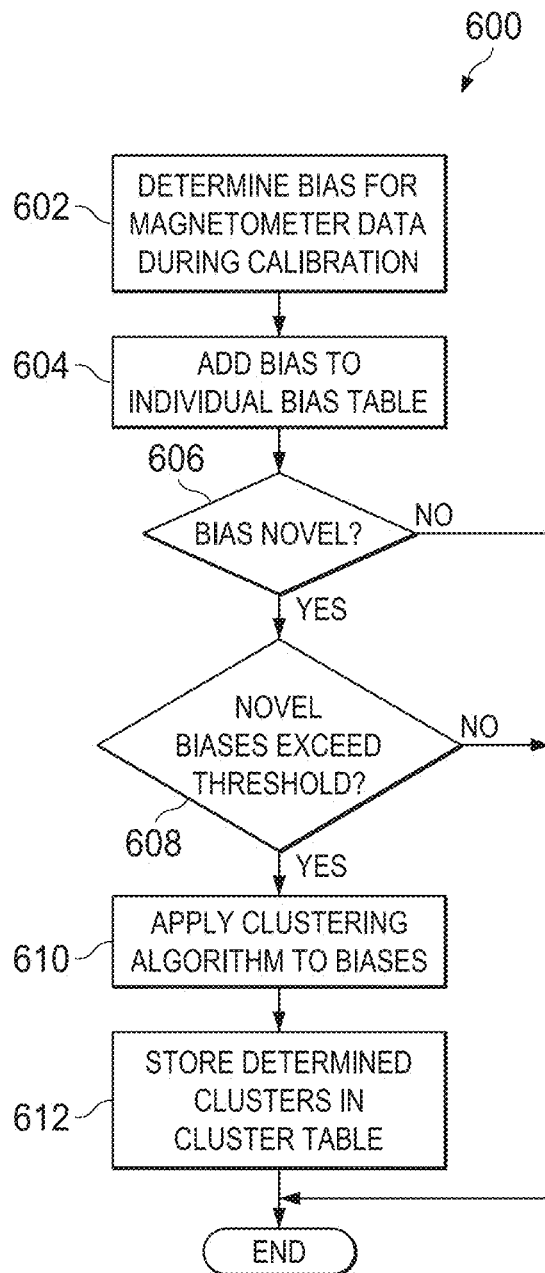
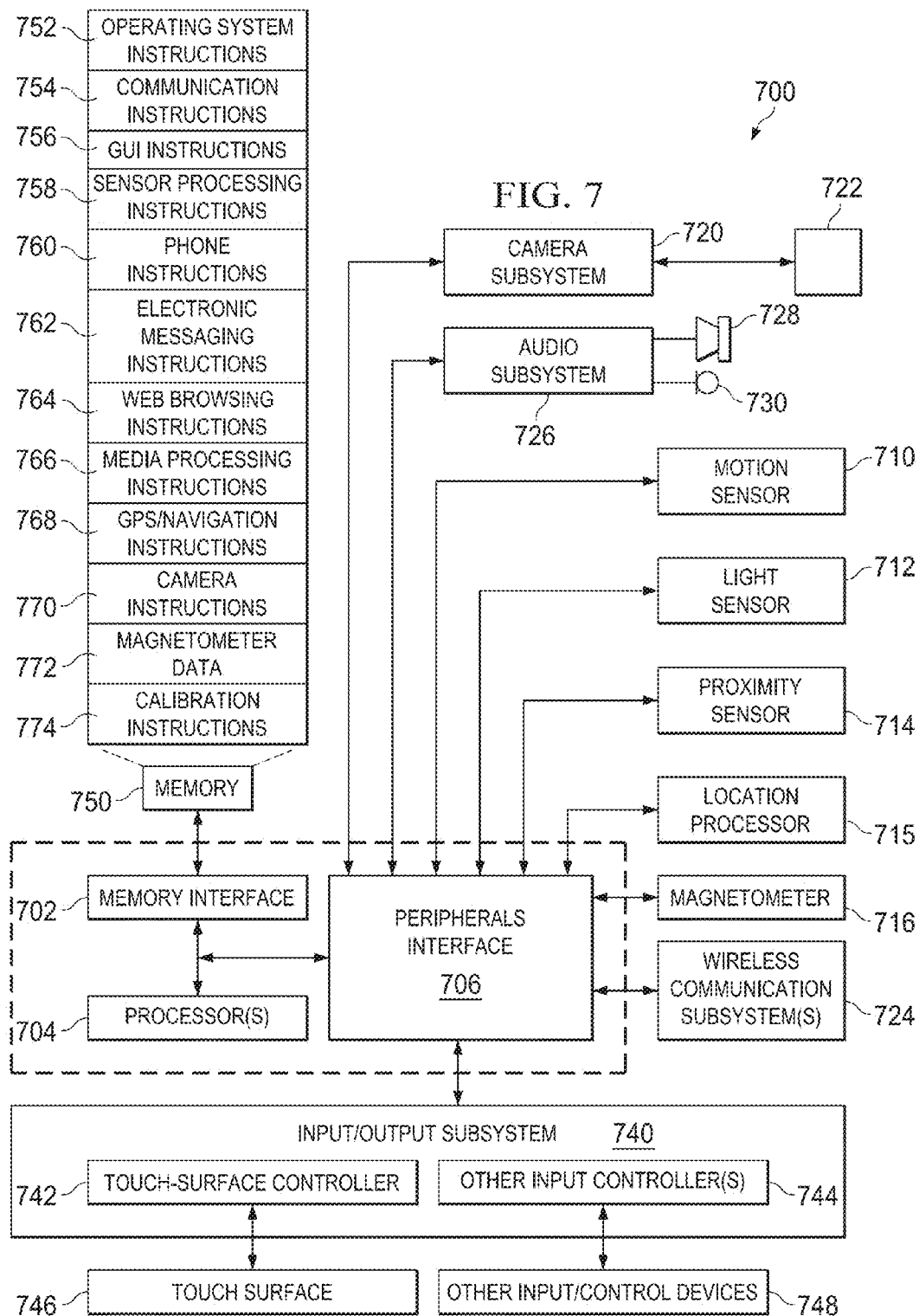
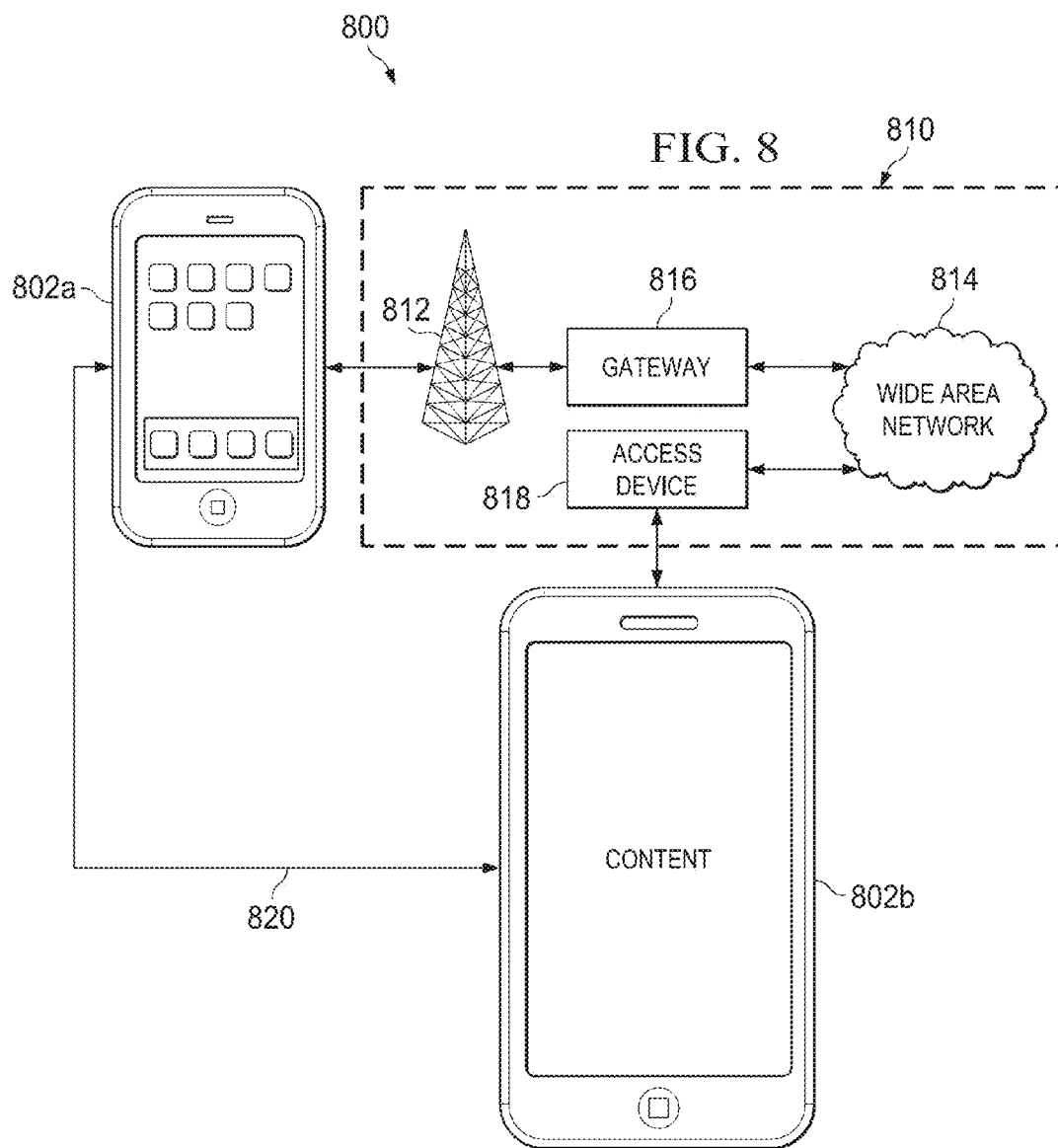


FIG. 6





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USING CLUSTERING TECHNIQUES TO IMPROVE MAGNETOMETER BIAS ESTIMATION

TECHNICAL FIELD

This subject matter is related to magnetometer bias estimation.

BACKGROUND

A mobile device such as a cellular phone or a smart phone, PDA, handheld computer, navigational device, gaming device, netbook, among others can be equipped with a magnetometer. Magnetic readings from the magnetometer can be used to provide a user with a direction, which may be a “heading” (typically given relative to the Earth’s true North), and/or an arrow pointing to true North. The direction information may be provided for the user’s own navigation knowledge, for example, to tell the user which way is north while the user is walking or driving in unfamiliar surroundings. The direction information can also be used by a navigation or map application that may be running on the mobile device.

The magnetometer obtains a measure of the magnetic field that is present in the immediate surroundings of the mobile device as a two or three-component vector in a Cartesian coordinate system using 2-axis or 3-axis magnetic sensors. The sensed magnetic field can contain a contribution of the Earth’s magnetic field and a contribution by a local interference field (device co-located interference fields). The latter is a magnetic field that is created by components in the local environment of the mobile device. This may include contributions by one or more magnetic field sources that are near the magnetic sensors, such as the magnet of a loudspeaker that is built into the mobile device. The interference field may also have a contribution due to one or more magnetic objects found in the external environment close to the device, such as when the user is driving an automobile, riding in a train or bus, or riding on a bicycle or motorcycle. In most cases, the interference field is not negligible relative to the Earth’s magnetic field. Therefore, a calibration procedure is needed to reduce the adverse impact of the interference field contribution from the sensors’ measurements to allow the magnetometer to calculate a more accurate direction.

There are several types of 3-axis calibration procedures. In one such technique, the user is instructed to rotate the mobile device (containing the magnetometer) according to a set of geometrically different orientations and azimuth angles, while measurements by the magnetometer and by an orientation sensor are collected and analyzed to isolate or quantify the interference field. The quantified interference field can then be subtracted from the measurement taken by the magnetic sensor to yield the Earth’s geomagnetic field. The Earth’s geomagnetic field can be further corrected to get the true north direction, such as correcting for magnetic variation (declination) due to the variation of the Earth’s magnetic field based on geographic location.

In another 3-axis calibration technique, rather than instruct the user to deliberately rotate the mobile device in a predetermined manner, measurements are collected from the magnetometer, continuously over a period of time, while the mobile device is being used or carried by the user. This can lead to random (albeit sufficient) rotations of the mobile device, such that the magnetometer measurements define a desired, generally spherical measurement space. The sphere

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is offset from the origin of a coordinate system for the Earth’s geomagnetic field vector by an unknown offset vector, which can represent a substantial part (if not all) of the interference field. Mathematical processing of the measurements can be performed to “re-center” the sphere by determining the offset vector. This technique is transparent to the user because the user is not required to go through a calibration procedure where the user deliberately rotates the device through a specified set of orientations.

The calibration techniques described above are effective but time consuming. As the user travels with the mobile device, the magnetometer will encounter different magnetic environments with varying local interference. These different magnetic environments can require a recalibration procedure and the calculation of a new offset vector. Even if the user returns to a previous location, a recalibration procedure may be required due to a change in the local interference field.

To avoid recalibrating the magnetometer for each use, a calibration database may be constructed with previously-calibrated readings. In these instances, raw magnetometer data is compared to a lookup table of the previously-calibrated readings, including thresholds, to determine matches with the raw magnetometer data. If a match is found, the bias offset for the matching calibrated reading may be applied to the raw magnetometer data to determine an estimated geomagnetic field. Though, the calibration data may include gaps such that no previously-calibrated readings match the raw calibration data. Also, the thresholds used to match the previously-calibrated readings are static.

SUMMARY

In some implementations, a computer-implemented method includes receiving a reading from a magnetometer of a mobile device. A cluster from a plurality of clusters of bias offsets generated from previously-calibrated readings is selected. The selected cluster has a representative bias offset, a mean of magnitudes in the selected cluster, and a magnitude threshold. An external magnetic field is estimated based on the reading and the representative bias offset for the selected cluster. Whether a magnitude of the estimated external field is within a magnitude range defined by the mean magnitude and the mean magnitude plus the magnitude threshold is determined.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates an exemplary Cartesian coordinate system describing the Earth’s geomagnetic field in accordance with some implementations.

FIG. 2 illustrates an exemplary 3-axis magnetometer in accordance with some implementations.

FIG. 3 illustrates an example system for evaluating readings against clustered data.

FIG. 4 is a three-dimensional graph illustrating clustering on bias vectors.

FIG. 5 is a flow chart illustrating an example method for comparing an estimated external field to clustered data.

FIG. 6 is a flow chart illustrating an example method for re-execution a clustering algorithm in response to a trigger event.

FIG. 7 is a block diagram of exemplary architecture of a mobile device employing the processes of FIGS. 5 and 6 in accordance with some implementations.

FIG. 8 is a block diagram of exemplary network operating environment for the device of FIG. 7.

DETAILED DESCRIPTION

Raw Magnetic Field—Overview

FIG. 1 illustrates an exemplary Cartesian coordinate system for describing the Earth's geomagnetic field \vec{E} in accordance with some implementations. The geomagnetic field vector \vec{E} can be described, in device coordinates, by the orthogonal components E_x (toward top of a mobile device), E_y (toward right side of mobile device) and E_z (back side of mobile device, positive downwards); the magnitude $|\vec{E}|$; and inclination (or dip relative to a horizontal line) I . Similarly, the gravitational acceleration vector \vec{g} can be described by the orthogonal components g_x (toward top of a mobile device), g_y (toward right side of mobile device) and g_z (back side of mobile device, positive downwards); and magnitude $|\vec{g}|$. The \vec{E} , \vec{g} , and the horizontal line are coplanar, and the intersection of \vec{g} and the horizontal line form a 90° angle. The magnitude $|\vec{E}|$, the magnitude $|\vec{g}|$, and the inclination angle I can be computed from the orthogonal components using the following equations:

$$|\vec{E}| = \sqrt{E_x^2 + E_y^2 + E_z^2}, \quad [1]$$

$$|\vec{g}| = \sqrt{g_x^2 + g_y^2 + g_z^2}, \text{ and} \quad [2]$$

$$I = 90 - \left(\cos^{-1} \left(\frac{\vec{E} \cdot \vec{g}}{|\vec{E}| |\vec{g}|} \right) * \frac{180}{\pi} \right) \quad [3]$$

The inclination angle I can be defined as the angle between the geomagnetic field \vec{E} and the Earth's gravitational acceleration vector \vec{g} . The most commonly used International System of Units (SI) unit of magnetic-field magnitude is the Tesla.

Overview of Magnetometers

FIG. 2 illustrates an exemplary 3-axis magnetometer in accordance with some implementations. In general, a magnetometer is an instrument that can sense the magnitude and direction of a magnetic field in its vicinity. Magnetometers can be 2-axis or 3-axis and the processes described here apply to both types of sensors. In the interest of brevity, only a 3-axis magnetometer is described.

In some implementations, 3-axis magnetometer sensor configuration 100 can be used to calculate a heading for a variety of applications, including applications running on a mobile device. For example, magnetometers may be used that require dead reckoning or headings, such as navigation applications for vehicles, aircraft, watercraft and mobile devices (e.g., smart phones). Sensor configuration 100 can include three magnetic field sensors 102, 104, 106 mounted orthogonally on a board, substrate or other mounting surface. Magnetic sensors 102, 104, 106 can be included in an integrated circuit (IC) package with or without other sensors, such as accelerometers and gyros.

Sensor configuration 100 can be deployed in a host system environment that contains interfering magnetic fields. Since the Earth's magnetic field is a weak field (~0.5

Gauss), other magnetic fields can interfere with the accuracy of sensors 102, 104, 106. For example, the sensors 102, 104, 106 may pick or otherwise detect magnetic fields generated by components of the mobile device, which may be referred to as bias offset. A calibration procedure can be deployed to isolate and remove the bias offset. One technique is to determine an offset vector which can be subtracted from sensor measurements to get accurate measurements of the Earth's magnetic field.

In one exemplary calibration procedure for a 3-axis magnetometer, each heading computation can be assumed to be made with a number of valid X, Y, and Z sensor readings which can be taken with a minimal delay between each reading. For this sensor configuration, sensors 102, 104, 106 are at right angles with respect to each other and lie level with respect to the Earth's surface. As discussed above, the positive end of the X-axis points to the top of the mobile device, the positive end of the Y-axis points to the right-side of the mobile device when facing the screen, and the positive end of the Z-axis points to backside of the mobile device. During calibration, two consecutive sensor readings may be made 180 degrees apart. These measurements can be represented by reading (R_{x1}, R_{y1}, R_{z1}) and reading (R_{x2}, R_{y2}, R_{z2}) , which are measurements of the raw magnetic field including Earth's magnetic field plus bias offset. The Earth's magnetic field in any given direction as measured with no interfering field can be represented by values (E_x, E_y, E_z) . Magnetic interference can be represented by values (B_x, B_y, B_z) . Using these mathematical conventions, the two sensor readings can be represented by

$$R_{x1} = E_x + B_x;$$

$$R_{y1} = E_y + B_y;$$

$$R_{z1} = E_z + B_z;$$

$$R_{x2} = -E_x + B_x;$$

$$R_{y2} = -E_y + B_y; \text{ and}$$

$$R_{z2} = -E_z + B_z. \quad [4]$$

Assuming the magnetometer is fixed with respect to the host system (e.g., a magnetometer installed in a mobile phone), the readings (R_{x1}, R_{y1}, R_{z1}) and (R_{x2}, R_{y2}, R_{z2}) taken during calibration may both contain substantially the same interference values (B_x, B_y, B_z) . Since the magnetometer readings taken during calibration are 180 degrees apart the readings of the Earth's magnetic field (E_x, E_y, E_z) are equal but opposite in sign $(-E_x, -E_y, -E_z)$. Solving the equations above for B_x, B_y , and B_z yields:

$$B_x = (R_{x1} + R_{x2})/2,$$

$$B_y = (R_{y1} + R_{y2})/2, \text{ and}$$

$$B_z = (R_{z1} + R_{z2})/2. \quad [5]$$

Using the determined bias offsets for each component, the Earth's magnetic field (E_x, E_y, E_z) may be determined by the following equations:

$$E_x = R_{x1} - B_x;$$

$$E_y = R_{y1} - B_y; \text{ and}$$

$$E_z = R_{z1} - B_z. \quad [6]$$

At any given position on Earth, a magnitude $|\vec{E}|$ is substantially constant, regardless of magnetometer orientation. Also, at any given position on Earth, the inclination

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angle I between the gravitational vector \vec{g} and the Earth's magnetic field \vec{E} is substantially constant because the orientation of the gravitational acceleration vector \vec{g} and the orientation of geomagnetic field vector \vec{E} are substantially constant.

A heading ψ of the mobile device may be calculated from the determined \vec{E} and \vec{g} using equations [7]-[11] as followed:

$$\theta = -\sin^{-1}\left(\frac{g_x}{|\vec{g}|}\right), \quad [7]$$

$$\phi = \sin^{-1}\left(\frac{g_y}{|\vec{g}|\cos\theta}\right), \quad [8]$$

$$X_h = E_x \cos(\theta) + E_y \sin(\theta) * \sin(\theta) - E_z \cos(\phi) * \sin(\theta) \quad [9]$$

$$Y_h = E_x \cos(\phi) + E_y \sin(\phi) \quad [10]$$

$$\psi = \tan^{-1}\left(\frac{Y_h}{X_h}\right). \quad [11]$$

The heading may be calibrated using other implementations. For example, the heading may also be calibrated based on the orientation of the device obtained from an accelerometer, inclination, GPS, and other types of corrections or calibrations.

If a magnetometer is included in a mobile device, such as a mobile phone, the bias offset may change. For example, if the user docks his mobile device (containing the magnetometer) in his car, magnetic objects in the car could change the local interference, which could result in the calibration offsets becoming invalid. If the offsets are invalid, then the magnetometer can perform a recalibration procedure to generate new offsets. This recalibration procedure can be a tedious process for the user if performed often and may require the user to manipulate the mobile device through a number of angles.

Example Cluster Evaluation of Magnetometer Data

FIG. 3 illustrates an example system 300 for cluster evaluation of magnetometer data. For example, the system 300 may store calibrated magnetometer data including magnitudes $|\vec{E}|$ of the geomagnetic field, inclination angle I , and associated bias offsets (B_x , B_y , B_z). As illustrated, the system 100 includes a magnetometer 302 for detecting magnetic fields, a magnetometer calibration module 304 for calibrating magnetometer data, magnetometer database 306 for storing calibrated magnetometer data, a clustering module 308 for determining clusters of the calibrated magnetometer data, clustered magnetometer database 310 for storing clustered data, and a cluster matching module 312 for determining whether magnetometer data matches any clusters in the clustered magnetometer database 310. In particular, the magnetometer 302 may be 2-axis or 3-axis magnetometer as discussed with respect to FIG. 2 that measures different components of the raw magnetic field (R_x , R_y , R_z) in, for example, device coordinates.

In response to a recalibration trigger event, the magnetometer 302 may pass magnetometer data to the magnetometer calibration module 304. A recalibration trigger event can be any event that triggers a recalibration procedure on the mobile device. The trigger event can be based on time, location, mobile device activity, an application request,

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magnetometer data, expiration of a time period, or other events. In connection with recalibration, the magnetometer calibration module 304 may determine a bias offsets (B_x , B_y , B_z) based on raw magnetometer reading (R_x , R_y , R_z) and determine the Earth's magnetic field vector \vec{E} based on the bias offset (B_x , B_y , B_z) and the raw magnetometer reading (R_x , R_y , R_z) as discussed with respect to FIG. 2. In addition, the magnetometer calibration module 304 may determine the magnitude $|\vec{E}|$ of the geomagnetic field and determine the inclination angle I based on the determined geomagnetic field vector \vec{E} and the gravitational vector \vec{g} . The magnetometer calibration module 304 may receive the gravitational vector \vec{g} from a location processor, accelerometer readings, or other sources.

Each time a calibration procedure is performed, the magnetometer calibration module 304 may store, in the magnetometer database 306, the magnitude $|\vec{E}|$, the inclination angle I , and associated bias offsets (B_x , B_y , B_z). As previously mentioned, the magnitude $|\vec{E}|$ and the inclination angle I for each location should be theoretically constant regardless of the position of the magnetometer on the Earth or its orientation. If these parameters are not constant then the bias offset may have changed. The magnetometer database 306 may store other parameters such as, for example, temperature, calibration level, a timestamp. The calibration level can be used to determine the accuracy or quality of a set of calibration data (e.g., offset values), so that an accurate set of calibration data are not overwritten with a less accurate set of calibration data. The timestamp can be used to manage entries in the magnetometer database 306. For example, the timestamp can be used with an "aging" algorithm for overwriting entries in the magnetometer database 306, so that magnetometer database 306 does not grow too large. In some implementations, entries with the oldest timestamp can be overwritten first. In some implementations, a count is kept for each entry in the magnetometer database 306 and may be incremented each time an entry is used to restore calibration offsets. The entries with the lowest count may be overwritten first. In some implementations, both timestamps and counts can be used for managing the magnetometer database 306. This constant property makes these Earth magnetic field parameters useful for determining the confidence of a match, as described in reference to FIG. 4.

The clustering module 308 can include any software, hardware, firmware, or combination thereof configured to execute a clustering algorithm on the bias offsets (B_x , B_y , B_z) stored in the magnetometer database 306 to form clusters. For example, the clustering module 308 may apply the well-known clustering algorithm known as quality threshold clustering algorithm to entries in the magnetometer database 306 to create clusters of bias offsets. Other clustering algorithm may be used such as connectivity based clustering, centroid-based clustering, distribution-based clustering, density-based clustering, or others. In general, cluster analysis or clustering assigns a set of objects into groups, i.e., clusters, so that the objects in the same cluster are more similar to each other based on one or more metrics than to objects in other clusters. In some implementations, the clusters may be based on the Euclidean distance between bias offset points. Further details of operations of clustering module 308 are described below in reference to FIG. 4.

The clustering module 308 stores the determined clusters in the clustered magnetometer database 310. For each cluster,

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ter, the clustering module **308** may determine a mean magnitude C_m of the Earth's geomagnetic field \vec{E} as follows:

$$C_m = \frac{\sum_{i=1}^N |\vec{E}_i|}{N} \quad [12]$$

where N is the number of geomagnetic field vectors \vec{E} in the cluster. Also, the clustering module **308** may determine a mean inclination angle C_a of the Earth's geomagnetic field \vec{E} as follows:

$$C_a = \frac{\sum_{i=1}^N I_i}{N} \quad [13]$$

where N is the number of geomagnetic fields \vec{E} in the cluster. In addition, the clustering module **308** may determine a magnitude threshold and an angle threshold. For example, the magnitude threshold may be based on the standard deviation of the magnitudes of the geomagnetic fields $|\vec{E}|$ in the cluster, and the angle threshold may be based on the standard deviation of the inclination angles in the cluster. In addition, the clustering module **308** may determine, for each cluster, a representative bias offset. For example, the clustering module **308** may determine, for each cluster, the geometric center of the cluster as the representative bias offset for the cluster. In some instances, the clustering module **308** determines, for each cluster, the mean of the biases as the center of the cluster. The clustering module **308** may use other statistical measures for determining the center of the cluster such as determining a median of the bias offsets of the cluster.

The cluster matching module **312** can include any software, hardware, firmware, or combination thereof for determining, for each of the clusters in the clustered magnetometer database **310**, whether magnetometer data from the magnetometer **302** satisfies the mean magnitude and magnitude threshold and the mean inclination angle and angle threshold. In particular, the cluster matching module **312** may identify the representative bias offset for each of the clusters and determine an estimated external field using the equations [6]. In other words, the cluster matching module **312** may, for each cluster, estimate the geomagnetic field \vec{E} using the following equation:

$$\vec{E} = \vec{R} - \vec{B} \quad [14]$$

where \vec{R} is the raw magnetic field vector determined by the magnetometer **302** and \vec{B} is the representative bias offset for the cluster. Once determined, the cluster matching module **312** may determine the magnitude $|\vec{E}|$ and the inclination angle I for the estimated geomagnetic field \vec{E} using the equations [1]-[3].

After the magnitude and inclination angle are determined for the estimated geomagnetic field \vec{E} for a cluster, the cluster matching module **312** may determine whether the estimated magnitude is within the range of the mean of the Earth's geomagnetic field to the mean plus the threshold for

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the cluster. In addition, the cluster matching module **312** may determine whether the estimated inclination angle I is within the range of the mean of the inclination angle to the mean plus the threshold for the cluster. If a match is not found, the cluster matching module **312** iteratively executes these calculations to determine if the estimated geomagnetic field matches any of the clusters in the clustered magnetometer database **310**. If a match with a cluster is found, an estimated heading ψ can be computed using the equations [7]-[11], the estimated geomagnetic field \vec{E} determined from the representative bias offset of the matching cluster, and the gravitational vector \vec{g} .

Clustering Overview

FIG. 4 is a three-dimensional graph **400** illustrating exemplary clustering techniques of bias offsets. In particular, the diagram **400** is a three-dimensional space based on the bias offset components (B_x , B_y , B_z). The clustering module **308** (as described in reference to FIG. 3) can apply quality threshold techniques to create exemplary clusters of bias offsets C1, C2, and C3. As illustrated, the graph **400** includes different clusters C1, C2, and C3 are illustrated in different shades of gray and clusters that include only a single point are illustrated in the same shade of gray.

The clustering module **308** can analyze the magnetometer database **306** as described above in reference to FIG. 3. The clustering module **208** can identify a first class of bias offsets having a first label (e.g., those labeled as "positive") and bias offsets having a second label (e.g., those labeled as "negative"). The clustering module **308** can identify a specified distance (e.g., a minimum distance) between a first class bias-offset point (e.g., "positive" bias-offset point **402**) and a second class motion feature (e.g., "negative" bias-offset point **404**). The clustering module **308** can designate the specified distance as a quality threshold (QT).

The clustering module **308** can select the first bias-offset point **402** to add to the first cluster C1. The clustering module **308** can then identify a second bias-offset point **404** whose distance to the first bias-offset point **402** is less than the quality threshold and, in response to satisfying the threshold, add the second bias-offset point **404** to the first cluster C1. The clustering module **308** can iteratively add bias-offset points to the first cluster C1 until all bias-offset points whose distances to the first bias-offset point **402** are each less than the quality threshold has been added to the first cluster C1.

The clustering module **308** can remove the bias-offset points in C1 from further clustering operations and select another bias-offset point (e.g., bias-offset points **406**) to add to a second cluster C2. The clustering module **308** can iteratively add bias-offset points to the second cluster C2 until all bias-offset points whose distances to the bias-offset point **406** are each less than the quality threshold have been added to the second cluster C2. The clustering module **308** can repeat the operations to create clusters C3, C4, and so on until all bias-offset points features are clustered.

The clustering module **308** can generate representative bias offsets for each cluster. In some implementations, the clustering module **308** can designate as the representative bias offsets the geometric center (e.g., mean of the bias offsets in the cluster) of the cluster such as the center **508** for cluster C1. The clustering module **308** may use other techniques for designating a bias-offset point as the representative bias offsets. For example, the clustering module **308** may identify an example that is closest to other samples. In

these instances, the clustering module 308 can calculate distances between pairs of bias-offset points in cluster C1 and determine a reference distance for each bias-offset point. The reference distance for a bias-offset point can be a maximum distance between the bias-offset point and another bias-offset point in the cluster. The clustering module 308 can identify a bias-offset point in cluster C1 that has the minimum reference distance and designate the bias-offset point as the bias offsets for cluster C1.

Example Process for Managing Clustered Data

FIGS. 5 and 6 are flow charts illustrating example methods 500 and 600 for managing clustered data in accordance with some implementations of the present disclosure. Methods 500 and 600 are described with respect to the system 300 of FIG. 3. Though, the associated system may use or implement any suitable technique for performing these and other tasks. These methods are for illustration purposes only and that the described or similar techniques may be performed at any appropriate time, including concurrently, individually, or in combination. In addition, many of the steps in these flowcharts may take place simultaneously and/or in different orders than as shown. Moreover, the associated system may use methods with additional steps, fewer steps, and/or different steps, so long as the methods remain appropriate.

Referring to FIG. 5, method 500 begins at step 502 where magnetometer data for the raw magnetic field is detected. For example, the magnetometer 302 in FIG. 3 may detect magnetic fields in device coordinates and pass the readings to the cluster matching module 312. At step 504, a plurality of clusters is identified. As for the example, the cluster matching module 312 may retrieve or otherwise identify clusters stored in the clustered magnetometer database 310. Next, at step 506, a representative bias offset is identified for an initial cluster. In some implementations, method 500 is iterated through all clusters such that the order may be determined based on any parameter such as timestamp, size, assigned indices, or others. An estimate of the external field is determined by the representative bias offset from the raw magnetic field at step 508. At step 510, the magnitude of the estimated external field is determined. Next, at step 512, a gravitational vector is identified. The inclination angle is determined, at step 514, based on an estimated external field vector and the gravitational vector. If the magnitude does not match the mean magnitude and threshold of the cluster or the inclination angle for the external field does not match the mean angle and threshold of the cluster at decisional step 516, then execution proceeds to decisional step 518. If another cluster is available for evaluation, then, at step 520, the representative bias offset for the next cluster is identified. If another cluster is not available to evaluate, the novel bias is stored in the database at step 522. Returning to decisional step 516, if both the magnitude of the estimated external field satisfy the magnitude threshold and the inclination angle of the estimated external field satisfy the angle threshold, a heading of the mobile device may be determined based on the estimated external field at step 524.

Referring to FIG. 6, method 600 begins at step 602 where the offset bias for magnetometer data is determined during calibration. For example, the magnetometer 302 may detect multiple points, and the magnetometer calibration module 304 may directly determine the bias offset using the multiple points. At step 604, the determined bias offset is added to the bias table. As for the example, the magnetometer calibration module 304 may store the bias offset in a lookup table stored

in the magnetometer database 306. If the determined bias offset is novel at decisional step 606, then execution proceeds to decisional step 608. For example, the magnetometer calibration module 304 may determine that the bias offset does not fall within the existing clusters. If the total number of bias offsets exceed a specified threshold (e.g., 2, 5, 10), then, at step 610, the clustering algorithm applied to the bias offset data stored in the magnetometer database 310 to determine new clusters. At step 612, the determined clusters are stored in a cluster table. As for the example, the clustering module 308 may apply the clustering algorithm on the magnetometer database 306, generate new clusters, and store the new clusters in a table of clustered magnetometer database 310. If either the bias offset falls within a cluster or the number of novel bias offsets have not exceed a threshold, then execution ends.

Example Mobile Device Architecture

FIG. 7 is a block diagram of exemplary architecture 700 of a mobile device including an electronic magnetometer. The mobile device 700 can include memory interface 702, one or more data processors, image processors and/or central processing units 704, and peripherals interface 706. Memory interface 702, one or more processors 704 and/or peripherals interface 706 can be separate components or can be integrated in one or more integrated circuits. Various components in mobile device architecture 700 can be coupled together by one or more communication buses or signal lines.

Sensors, devices, and subsystems can be coupled to peripherals interface 706 to facilitate multiple functionalities. For example, motion sensor 710, light sensor 712, and proximity sensor 714 can be coupled to peripherals interface 706 to facilitate orientation, lighting, and proximity functions of the mobile device. Location processor 715 (e.g., GPS receiver) can be connected to peripherals interface 706 to provide geopositioning. Electronic magnetometer 716 (e.g., an integrated circuit chip) can also be connected to peripherals interface 706 to provide data that can be used to determine the direction of magnetic North.

Camera subsystem 720 and Optical sensor 722, e.g., a charged coupled device (CCD) or a complementary metal-oxide semiconductor (CMOS) optical sensor, can be utilized to facilitate camera functions, such as recording photographs and video clips.

Communication functions can be facilitated through one or more wireless communication subsystems 724, which can include radio frequency receivers and transmitters and/or optical (e.g., infrared) receivers and transmitters. The specific design and implementation of communication subsystem 724 can depend on the communication network(s) over which the mobile device is intended to operate. For example, the mobile device may include communication subsystems 724 designed to operate over a GSM network, a GPRS network, an EDGE network, a Wi-Fi or WiMax network, and a Bluetooth™ network. In particular, wireless communication subsystems 724 may include hosting protocols such that the mobile device may be configured as a base station for other wireless devices.

Audio subsystem 726 can be coupled to speaker 728 and microphone 730 to facilitate voice-enabled functions, such as voice recognition, voice replication, digital recording, and telephony functions. Note that speaker 728 could introduce magnetic interference to the magnetometer, as described in reference to FIGS. 1-2.

I/O subsystem **740** can include touch surface controller **742** and/or other input controller(s) **744**. Touch surface controller **742** can be coupled to touch surface **746**. Touch surface **746** and touch surface controller **742** can, for example, detect contact and movement or break thereof using any of a plurality of touch sensitivity technologies, including but not limited to capacitive, resistive, infrared, and surface acoustic wave technologies, as well as other proximity sensor arrays or other elements for determining one or more points of contact with touch surface **746**.

Other input controller(s) **744** can be coupled to other input/control devices **748**, such as one or more buttons, rocker switches, thumb-wheel, infrared port, USB port, docking station and/or a pointer device such as a stylus. The one or more buttons (not shown) can include an up/down button for volume control of speaker **728** and/or microphone **730**.

In one implementation, a pressing of the button for a first duration may disengage a lock of touch surface **746**; and a pressing of the button for a second duration that is longer than the first duration may turn power to the mobile device on or off. The user may be able to customize a functionality of one or more of the buttons. Touch surface **746** can, for example, also be used to implement virtual or soft buttons and/or a keyboard.

In some implementations, the mobile device can present recorded audio and/or video files, such as MP3, AAC, and MPEG files. In some implementations, the mobile device can include the functionality of an MP3 player, such as an iPod Touch™.

Memory interface **702** can be coupled to memory **750**. Memory **750** can include high-speed random access memory and/or non-volatile memory, such as one or more magnetic disk storage devices, one or more optical storage devices, and/or flash memory (e.g., NAND, NOR). Memory **750** can store operating system **752**, such as Darwin, RTXC, LINUX, UNIX, OS X, WINDOWS, or an embedded operating system such as VxWorks. Operating system **752** may include instructions for handling basic system services and for performing hardware dependent tasks. In some implementations, operating system **752** can be a kernel (e.g., UNIX kernel).

Memory **750** may also store communication instructions **754** to facilitate communicating with one or more additional devices, one or more computers and/or one or more servers. Memory **750** may include graphical user interface instructions **756** to facilitate graphic user interface processing; sensor processing instructions **758** to facilitate sensor-related processing and functions; phone instructions **760** to facilitate phone-related processes and functions; electronic messaging instructions **762** to facilitate electronic-messaging related processes and functions; web browsing instructions **764** to facilitate web browsing-related processes and functions; media processing instructions **766** to facilitate media processing-related processes and functions; GPS/Navigation instructions **768** to facilitate GPS and navigation-related processes and instructions; camera instructions **770** to facilitate camera-related processes and functions; magnetometer data **772** and calibration instructions **774** to facilitate magnetometer calibration, as described in reference to FIG. 2. In some implementations, GUI instructions **756** and/or media processing instructions **766** implement the features and operations described in reference to FIGS. 1-6.

Memory **750** may also store other software instructions (not shown), such as web video instructions to facilitate web video-related processes and functions; and/or web shopping instructions to facilitate web shopping-related processes and

functions. In some implementations, media processing instructions **766** are divided into audio processing instructions and video processing instructions to facilitate audio processing-related processes and functions and video processing-related processes and functions, respectively. An activation record and International Mobile Equipment Identity (IMEI) or similar hardware identifier can also be stored in memory **750**.

Each of the above identified instructions and applications can correspond to a set of instructions for performing one or more functions described above. These instructions need not be implemented as separate software programs, procedures, or modules. Memory **750** can include additional instructions or fewer instructions. Furthermore, various functions of the mobile device may be implemented in hardware and/or in software, including in one or more signal processing and/or application specific integrated circuits.

The disclosed and other embodiments and the functional operations described in this specification can be implemented in digital electronic circuitry, or in computer software, firmware, or hardware, including the structures disclosed in this specification and their structural equivalents, or in combinations of one or more of them. The disclosed and other embodiments can be implemented as one or more computer program products, i.e., one or more modules of computer program instructions encoded on a computer-readable medium for execution by, or to control the operation of, data processing apparatus. The computer-readable medium can be a machine-readable storage device, a machine-readable storage substrate, a memory device, or a combination of one or more them. The term "data processing apparatus" means all apparatus, devices, and machines for processing data, including by way of example a programmable processor, a computer, or multiple processors or computers. The apparatus can include, in addition to hardware, code that creates an execution environment for the computer program in question, e.g., code that constitutes processor firmware, a protocol stack, a database management system, an operating system, or a combination of one or more of them.

A computer program (also known as a program, software, software application, script, or code) can be written in any form of programming language, including compiled or interpreted languages, and it can be deployed in any form, including as a stand-alone program or as a module, component, subroutine, or other unit suitable for use in a computing environment. A computer program does not necessarily correspond to a file in a file system. A program can be stored in a portion of a file that holds other programs or data (e.g., one or more scripts stored in a markup language document), in a single file dedicated to the program in question, or in multiple coordinated files (e.g., files that store one or more modules, sub-programs, or portions of code). A computer program can be deployed to be executed on one computer or on multiple computers that are located at one site or distributed across multiple sites and interconnected by a communication network.

The processes and logic flows described in this specification can be performed by one or more programmable processors executing one or more computer programs to perform functions by operating on input data and generating output. The processes and logic flows can also be performed by, and apparatus can also be implemented as, special purpose logic circuitry, e.g., an FPGA (field programmable gate array) or an ASIC (application-specific integrated circuit).

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Processors suitable for the execution of a computer program include, by way of example, both general and special purpose microprocessors, and any one or more processors of any kind of digital computer. Generally, a processor will receive instructions and data from a read-only memory or a random access memory or both. The essential elements of a computer are a processor for performing instructions and one or more memory devices for storing instructions and data. Generally, a computer will also include, or be operatively coupled to receive data from or transfer data to, or both, one or more mass storage devices for storing data, e.g., magnetic, magneto-optical disks, or optical disks. However, a computer need not have such devices. Computer-readable media suitable for storing computer program instructions and data include all forms of non-volatile memory, media and memory devices, including by way of example semiconductor memory devices, e.g., EPROM, EEPROM, and flash memory devices; magnetic disks, e.g., internal hard disks or removable disks; magneto-optical disks; and CD-ROM and DVD-ROM disks. The processor and the memory can be supplemented by, or incorporated in, special purpose logic circuitry.

To provide for interaction with a user, the disclosed embodiments can be implemented on a computer having a display device, e.g., a CRT (cathode ray tube) or LCD (liquid crystal display) monitor, for displaying information to the user and a keyboard and a pointing device, e.g., a mouse or a trackball, by which the user can provide input to the computer. Other kinds of devices can be used to provide for interaction with a user as well; for example, feedback provided to the user can be any form of sensory feedback, e.g., visual feedback, auditory feedback, or tactile feedback; and input from the user can be received in any form, including acoustic, speech, or tactile input.

The disclosed embodiments can be implemented in a computing system that includes a back-end component, e.g., as a data server, or that includes a middleware component, e.g., an application server, or that includes a front-end component, e.g., a client computer having a graphical user interface or a Web browser through which a user can interact with an implementation of what is disclosed here, or any combination of one or more such back-end, middleware, or front-end components. The components of the system can be interconnected by any form or medium of digital data communication, e.g., a communication network. Examples of communication networks include a local area network ("LAN") and a wide area network ("WAN"), e.g., the Internet.

While this specification contains many specifics, these should not be construed as limitations on the scope of what being claims or of what may be claimed, but rather as descriptions of features specific to particular embodiments. Certain features that are described in this specification in the context of separate embodiments can also be implemented in combination in a single embodiment. Conversely, various features that are described in the context of a single embodiment can also be implemented in multiple embodiments separately or in any suitable subcombination. Moreover, although features may be described above as acting in certain combinations and even initially claimed as such, one or more features from a claimed combination can in some cases be excised from the combination, and the claimed combination may be directed to a subcombination or variation of a subcombination.

Similarly, while operations are depicted in the drawings in a particular order, this should not be understood as requiring that such operations be performed in the particular order

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shown or in sequential order, or that all illustrated operations be performed, to achieve desirable results. In certain circumstances, multitasking and parallel processing may be advantageous. Moreover, the separation of various system components in the embodiments described above should not be understood as requiring such separation in all embodiments, and it should be understood that the described program components and systems can generally be integrated together in a single software product or packaged into multiple software products.

Exemplary Operating Environment

FIG. 8 is a block diagram of exemplary network operating environment 800 for the mobile devices implementing motion pattern classification and gesture recognition techniques. Mobile devices 802a and 802b can, for example, communicate over one or more wired and/or wireless networks 810 in data communication. For example, a wireless network 812, e.g., a cellular network, can communicate with a wide area network (WAN) 814, such as the Internet, by use of a gateway 816. Likewise, an access device 818, such as an 802.11g wireless access device, can provide communication access to the wide area network 814.

In some implementations, both voice and data communications can be established over wireless network 812 and the access device 818. For example, mobile device 802a can place and receive phone calls (e.g., using voice over Internet Protocol (VoIP) protocols), send and receive e-mail messages (e.g., using Post Office Protocol 3 (POP3)), and retrieve electronic documents and/or streams, such as web pages, photographs, and videos, over wireless network 812, gateway 816, and wide area network 814 (e.g., using Transmission Control Protocol/Internet Protocol (TCP/IP) or User Datagram Protocol (UDP)). Likewise, in some implementations, the mobile device 802b can place and receive phone calls, send and receive e-mail messages, and retrieve electronic documents over the access device 818 and the wide area network 814. In some implementations, mobile device 802a or 802b can be physically connected to the access device 818 using one or more cables and the access device 818 can be a personal computer. In this configuration, mobile device 802a or 802b can be referred to as a "tethered" device.

Mobile devices 802a and 802b can also establish communications by other means. For example, wireless mobile device 802a can communicate with other wireless devices, e.g., other mobile devices 802a or 802b, cell phones, etc., over the wireless network 812. Likewise, mobile devices 802a and 802b can establish peer-to-peer communications 820, e.g., a personal area network, by use of one or more communication subsystems, such as the Bluetooth™ communication devices. Other communication protocols and topologies can also be implemented.

The mobile device 802a or 802b can, for example, communicate with one or more services 830 and 840 over the one or more wired and/or wireless networks. For example, one or more motion training services 830 can be used to determine one or more motion patterns. Motion pattern service 840 can provide the one or more one or more motion patterns to mobile devices 802a and 802b for recognizing gestures.

Mobile device 802a or 802b can also access other data and content over the one or more wired and/or wireless networks. For example, content publishers, such as news sites, Rally Simple Syndication (RSS) feeds, web sites, blogs, social networking sites, developer networks, etc., can

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be accessed by mobile device **802a** or **802b**. Such access can be provided by invocation of a web browsing function or application (e.g., a browser) in response to a user touching, for example, a Web object.

Particular embodiments of the subject matter described in this specification have been described. Other embodiments are within the scope of the following claims. For example, the actions recited in the claims can be performed in a different order and still achieve desirable results. As one example, the processes depicted in the accompanying figures do not necessarily require the particular order shown, or sequential order, to achieve desirable results. In certain implementations, multitasking and parallel processing may be advantageous.

What is claimed is:

1. A computer-implemented method, comprising:
 - receiving, by a mobile device, a reading from a magnetometer of the mobile device;
 - selecting, by a processor of the mobile device, a cluster from a plurality of clusters of bias offsets, wherein:
 - each of the clusters includes a plurality of bias offsets including a representative bias offset,
 - the plurality of clusters are generated by clustering on bias vectors calculated from previous magnetometer readings, and
 - selecting the cluster from the clusters includes matching the reading from the magnetometer to a respective set of one or more mean values of each of the clusters and identifying the cluster from the clusters according to a respective set of one or more threshold values;
 - estimating, by the processor, a current external magnetic field based on the reading and the representative bias offset for the selected cluster; and
 - determining, by the processor, a heading for the mobile device using the estimated current external field.
2. The computer-implemented method of claim 1, further comprising:
 - determining that a magnitude of the estimated current external field is within a magnitude range defined by a mean magnitude for the selected cluster and the mean magnitude plus a magnitude threshold;
 - determining a gravitational vector;
 - determining an inclination angle between the gravitational vector and the estimated current external magnetic field; and
 - determining that the inclination angle is within an angle range defined by a mean inclination angle for the selected cluster and the mean angle plus an angle threshold.
3. The computer-implemented method of claim 2, further comprising:
 - determining the estimated current external magnetic field is not within the magnitude range or the inclination angle is not in the angle range;
 - iteratively estimating the current external field using representative bias offsets for different clusters in the plurality of clusters; and
 - for each iteration, determining whether the estimated current external field is in the magnitude range or the inclination angle is in the angle range for a cluster selected during that iteration.
4. The computer-implemented method of claim 1, further comprising:
 - receiving calibrated magnetometer data including a bias offset;
 - comparing the bias offset to the plurality of clusters;

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determining the bias offset does not match any cluster in the plurality of clusters; and
identifying the bias offset as novel.

5. The computer-implemented method of claim 4, in response to determining a number of novel bias offsets exceeds a specified number, automatically applying a clustering technique to historical magnetometer data to generate new clusters of bias offsets.

6. The computer-implemented method of claim 1, wherein the plurality of clusters are formed using a quality threshold clustering.

7. The computer-implemented method of claim 1, wherein the current external magnetic field is estimated by subtracting the representative bias offset for the selected cluster from the readings.

8. The computer-implemented method of claim 1, wherein the magnitude threshold is based on a standard deviation of magnitudes in the selected cluster.

9. A computer program product encoded on a tangible, non-transitory storage medium, the product comprising computer readable instructions for causing one or more processors to perform operations comprising:

- receiving, by a mobile device, a reading from a magnetometer of the mobile device;

- selecting, by a processor of the mobile device, a cluster from a plurality of clusters of bias offsets, wherein:

- each of the clusters includes a plurality of bias offsets including a representative bias offset,

- the plurality of clusters are generated by clustering on bias vectors calculated from previous magnetometer readings, and

- selecting the cluster from the clusters includes matching the reading from the magnetometer to a respective set of one or more mean values of each of the clusters and identifying the cluster from the clusters according to a respective set of one or more threshold values;

- estimating, by the processor, a current external magnetic field based on the reading and a representative bias offset for the selected cluster; and

- determining, by the processor, a heading for the mobile device using the estimated current external field.

10. The computer program product of claim 9, the instructions further comprising:

- determining that a magnitude of the estimated current external field is within a magnitude range defined by a mean magnitude for the selected cluster and the mean magnitude plus a magnitude threshold;

- determining a gravitational vector;

- determining an inclination angle between the gravitational vector and the estimated current external magnetic field; and

- determining that the inclination angle is within an angle range defined by a mean inclination angle for the selected cluster and the mean angle plus an angle threshold.

11. The computer program product of claim 9, the instructions further comprising:

- determining the estimated current external magnetic field is not within the magnitude range or the inclination angle is not in the angle range;

- iteratively estimating the current external field using representative bias offsets for different clusters in the plurality of clusters; and

- for each iteration, determining whether the estimated current external field is in the magnitude range or the

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inclination angle is in the angle range for a cluster selected during that iteration.

12. The computer program product of claim 9, the instructions further comprising:

receiving calibrated magnetometer data including a bias offset;

comparing the bias offset to the plurality of clusters; determining the bias offset does not match any cluster in the plurality of clusters; and

identifying the bias offset as novel.

13. The computer program product of claim 12, in response to determining a number of novel bias offsets exceeds a specified number, the instructions further comprising automatically applying a clustering technique to historical magnetometer data to generate new clusters of bias offsets.

14. The computer program product of claim 9, wherein the plurality of clusters are formed using a quality threshold clustering.

15. The computer program product of claim 9, wherein the current external magnetic field is estimated by subtracting the representative bias offset for the selected cluster from the readings.

16. The computer program product of claim 9, wherein the magnitude threshold is based on a standard deviation of magnitudes in the selected cluster.

17. A mobile device, comprising:

a magnetometer;

memory configured to a plurality of clusters of bias offsets generated from previously-calibrated readings; and one or more processors configured to perform operations comprising:

receiving a reading from the magnetometer;

selecting a cluster from a plurality of clusters of bias offsets, wherein:

each of the clusters includes a plurality of bias offsets including a representative bias offset,

the plurality of clusters are generated by clustering on bias vectors calculated from previous magnetometer readings, and

selecting the cluster from the clusters includes matching the reading from the magnetometer to a respective set of one or more mean values of each of the clusters and identifying the cluster from the clusters according to a respective set of one or more threshold values;

estimating a current external magnetic field based on the reading and the representative bias offset for the selected cluster; and

determining a heading for the mobile device using the estimated current external field.

18. The mobile device of claim 17, the processors further configured to:

determine that a magnitude of the estimated current external field is within a magnitude range defined by a mean magnitude for the selected cluster and the mean magnitude plus a magnitude threshold;

determine a gravitational vector;

determine an inclination angle between the gravitational vector and the estimated current external magnetic field; and

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determine that the inclination angle is within an angle range defined by a mean inclination angle for the selected cluster and the mean angle plus an angle threshold.

19. The mobile device of claim 17, the processors further configured to:

determine the estimated current external magnetic field is not within the magnitude range or the inclination angle is not in the angle range;

iteratively estimate the current external field using representative bias offsets for different clusters in the plurality of clusters; and

for each iteration, determine whether the estimated current external field is in the magnitude range or the inclination angle is in the angle range for a cluster selected during that iteration.

20. The mobile device of claim 17, the processors further configured to:

receive calibrated magnetometer data including a bias offset;

compare the bias offset to the plurality of clusters;

determine the bias offset does not match any cluster in the plurality of clusters; and

identify the bias offset as novel.

21. The mobile device of claim 20, in response to determine a number of novel basis offsets exceeds a specified number, the processors further configured to automatically apply a clustering technique to historical magnetometer data to generate new clusters of bias offsets.

22. The mobile device of claim 17, wherein the plurality of clusters are formed using a quality threshold clustering.

23. The mobile device of claim 17, wherein the current external magnetic field is estimated by subtracting the representative bias offset for the selected cluster from the readings.

24. The mobile device of claim 17, wherein the magnitude threshold is based on a standard deviation of magnitudes in the selected cluster.

25. The mobile device of claim 17, wherein each set of one or more mean values includes at least one of a mean magnitude value or a mean inclination angle value.

26. The mobile device of claim 25, wherein matching the reading from the magnetometer to a respective set of one or more mean values of each of the clusters and identifying the cluster from the clusters according to a respective set of one or more threshold values comprise, for each cluster:

determining a magnitude and an inclination angle for an estimated geomagnetic field; and

for each cluster:

determine whether the magnitude of the estimated geomagnetic field is within a range between the mean magnitude value of the cluster and the mean magnitude value plus a threshold value for the cluster;

determine whether the inclination angle of the estimated geomagnetic field is within a range between the mean inclination angle of the cluster and the mean inclination angle plus a threshold value for the cluster; and

identifying the cluster upon determining that both the magnitude and the inclination angle are in range.

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